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RESEARCH MEMORANDUM

CLASSIFICATION CHANGED

PRELIMINARY NOTE ON A CORRELATION OF BOUNDARY-LAYER TRANSITION RESULTS ON HIGHLY COOLED BLUNT BODIES

By Richard J. Wisniewski

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Cleveland, Ohio

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ABSTRACT

Transition data on highly cooled blunt bodies are correlated in terms of the ratio of wall to local-stream enthalpy, Reynolds number based on displacement thickness, and location of transition. The proposed correlation, although not sensitive enough to predict the exact location of transition does predict the enthalpy ratio below which very early transition on blunt bodies is expected. The correlation is not altered by moderate amounts of surface roughness; however, the location of transition may well be affected by roughness.

INDEX HEADINGS

Flow, Laminar 1.1.3.1

Flow, Turbulent 1.1.3.2

Heat Transfer, Aerodynamic 1.1.4.2

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

PRELIMINARY NOTE ON A CORRELATION OF BOUNDARY-LAYER TRANSITION RESULTS ON HIGHLY COOLED BLUNT BODIES

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SUMMARY

Boundary-layer transition data on highly cooled blunt bodies are correlated in terms of the ratio of wall to local-stream enthalpy, Reynolds number based on displacement thickness, and location of transition. The proposed correlation is not sufficiently sensitive to predict the exact location of transition, but it does predict the enthalpy ratio below which very early transition on blunt bodies is expected. The correlation is not altered by moderate amounts of surface roughness; however, the location of transition may well be affected by roughness.

INTRODUCTION

The problem of transition on blunt, highly cooled bodies in hypersonic flow has been one of particular concern ever since Allen and Eggers (ref. 1) first proposed high-drag configurations for atmospheric reentry of ballistic missiles. In recent years, a respectable amount of experimental transition data on such bodies has been obtained; in fact, the Lockheed X-17 reentry test vehicle program was initiated for the specific purpose of obtaining transition data under conditions simulating actual reentry of an intercontinental ballistic missile. The Pilotless Aircraft Research Division (PARD) of the NACA Langley laboratory and the Hypersonic Test Vehicle (HTV) program of Aerophysics Development Corporation also have obtained a substantial amount of transition data on cooled blunt bodies.

As a whole, these data demonstrate two rather disturbing facts: First, transition on a cooled blunt body occurs at very low Reynolds numbers; and second, the results obtained under apparently similar conditions are often vastly different and quite contradictory.

Correlations of these results were attempted by Stewart and Donaldson (ref. 2) and by Tellep and Hoshizaki (ref. 3). The correlation given in reference 3 indicates that surface roughness is exceedingly important

and that transition can be delayed by keeping the body very smooth; however, this correlation was not wholly successful for all X-17 reentry data. In many instances, it failed completely when transition during the ascending portion of the X-17 trajectory was considered or when data other than the X-17 data were used.

Stewart and Donaldson's correlation (ref. 2) is plotted as wall to local-stream enthalpy ratio against transition Reynolds number based on momentum thickness, with body position as a parameter. In this representation, surface roughness did not significantly alter the correlation. This correlation was quite adequate for all X-17 reentry data, but it does not satisfactorily correlate the X-17 exit data or portions of the HTV and PARD data. Reference 2 also implies, as was suggested in reference 4, that the early transition on blunt bodies and the transition reversal on slender bodies (ref. 5) are essentially the same phenomenon.

The purpose of this report is to present a new correlation of the aforementioned data. Not all of the consequences or implications of this correlation are understood as yet, and contradictory evidence may exist. However, in view of the urgent need for a method of predicting transition on highly cooled blunt bodies, it was felt that distribution of this preliminary report is warranted.

SYMBOLS

The following symbols are used in this report:

A cross-sectional (frontal) area of body, sq ft

C_D body drag coefficient

d body diameter, ft

H form factor, δ^*/θ

H_{tr} low-speed form factor (ref. 7)

h enthalpy

k roughness height, microin.

M Mach number

$\widetilde{Re}$ integrated Reynolds number, $\dfrac{\int_0^s \rho_e \mu_e V_e r_0^2 ds}{\mu_e^2 r_0^2}$

$Re_{D,1}$ free-stream Reynolds number based on body diameter, $\frac{\rho_1 V_1 d}{\mu_1}$

Re_{δ^*} displacement-thickness Reynolds number, $\frac{\rho_e V_e \delta^*}{\mu_e}$

Re_θ momentum-thickness Reynolds number, $\frac{\rho_e V_e \theta}{\mu_e}$

r_n nose radius, ft

r_0 axial radius, ft

s surface distance, ft

T total temperature, °R

t time, sec

V velocity, ft/sec

W weight, lb

α angle of flight path to horizontal, deg

β pressure-gradient parameter

γ_{eff} effective ratio of specific heats (given as γ_e in ref. 3)

δ^* displacement thickness, ft

θ momentum thickness, microin.

θ_c cone half-angle

μ viscosity

ρ density

φ_T angle between normal to body surface and free-stream direction

Subscripts:

e local free-stream conditions at edge of boundary layer

TR transition conditions

w conditions at wall

0 stagnation conditions behind shock

1 free-stream conditions ahead of shock

REDUCTION OF DATA

The Location of Transition

The present correlation uses data obtained on hemispheres, hemisphere-cones, and slightly blunted cone-cylinders; all of the data used in this report are listed in table I. Transition locations during the X-17 test vehicle reentry and the PARD and HTV flight tests are given in reference 2. During the exit phase of the X-17 R-9 flight (ref. 3) transition was determined from a plot of the heating rates. However, the exact time of transition was difficult to determine because of the low heating rates and uncertainties in analyzing the data. Hence, the transition points listed in table I for the exit phase of the R-9 flight are subject to question. Transition locations for the NACA Lewis laboratory data are given in references 5 and 6.

Displacement-Thickness Reynolds Number

In addition to the quantities presented in reference 2, the Reynolds number based on displacement thickness is needed for the present correlation. This was obtained from the momentum-thickness Reynolds number as follows:

$$Re_{\delta^*} = HRe_\theta \tag{1}$$

where

$$H = \frac{\delta^*}{\theta} = \frac{T_0}{T_e}(H_{tr} + 1) - 1$$

$$Re_\theta = 0.664(\tilde{Re})^{1/2}$$

The function H_{tr} depends on the pressure-gradient parameter β and is obtained from reference 7. Curves of $H_{tr} + 1$ as a function of β and the wall to total enthalpy ratio of h_w/h_0 are plotted in figure 1. The value of β for the angular position φ_T on a hemisphere or hemisphere segment was approximated by the values listed in the following table:

φ_T	0	20	45	60	90
β	0.50	0.50	0.75	1.03	2.00

Along conical bodies, β equals zero. The temperature ratio T_0/T_e was approximated by

$$\frac{T_0}{T_e} \cong 1 + \frac{\gamma_{eff} - 1}{2} M_e^2 \cong \frac{h_0}{h_e} \tag{2}$$

where the effective specific-heat ratio γ_{eff} was taken as 1.40 for $M_1 < 5$ and was varied as suggested in reference 3 for $M_1 > 5$. Local external Mach numbers M_e were found with the aid of modified Newtonian flow theory and perfect gas relations. Computed values of Re_{δ^*} are also given in table I, in which many of the values are of slide-rule accuracy only.

CORRELATION OF DATA

Transition Reynolds Number Based on Displacement Thickness

The correlations of blunt-body transition data proposed in the past were generally based on momentum-thickness Reynolds number. A typical plot of wall to local-stream enthalpy ratio as a function of the transition momentum-thickness Reynolds number $Re_{\theta,TR}$ is shown in figure 2. Although this correlation may be satisfactory for any given set of transition points, it is not adequate when data from many sources are compared. In particular, it is apparent that the same value of $Re_{\theta,TR}$ is obtained for an appreciable range of enthalpy ratios.

There is no analytical reason why transition should be described by the momentum thickness. Some other length that can describe the growth or shape of the boundary layer may be more satisfactory insofar as transition is concerned. Furthermore, if some arbitrarily chosen length can be used successfully in correlating the data presented in figure 2, then that length must depend on temperature. The displacement thickness is such a length.

In figure 3(a), the X-17 reentry data obtained on hemispheres are shown on a plot of wall to local-stream enthalpy ratio against transition Reynolds number based on displacement thickness. These data are well correlated, and it is apparent that surface finishes from less than 2 microinches to 30 microinches are represented by a single curve. From figure 3(b) the same conclusions can be drawn for reentry data obtained on the GE 3.1 shape.

In figure 4, the X-17, PARD, and HTV data of reference 2 and the NACA Lewis laboratory results of reference 6 are presented in terms of $Re_{\delta^*,TR}$. Only the results obtained on segments of hemispheres are

included in figure 4; all data points shown in figure 2 (with the exception of three points yielding negative displacement thickness) are represented in this figure. It is apparent that the correlation is an improvement over the $Re_{\theta,TR}$ correlation (fig. 2) but still is far from adequate. A careful examination of the individual points plotted in figure 4 indicates that, as suggested by Stewart and Donaldson (ref. 2), body position also affects transition. It is rather evident, however, that the results presented in terms of $Re_{\delta^*,TR}$ are not sensitive to moderate amounts of roughness.

Also shown in figure 4 are the transition-reversal data obtained on a slender, slightly blunted cone-cylinder (ref. 5). Although body position again enters into these results, the trend of the blunt-body transition data and the slender-body reversal data appears to be similar.

Modified Displacement-Thickness Reynolds Number

In figure 5, the effect of body position on transition is taken into account by dividing the abscissa by s/r_n, which, for a hemisphere, corresponds to the angular position along the nose. All available X-17 reentry data and PARD, HTV, and NACA Lewis data on cooled hemispheres are included in figure 5; surface finishes up to 30 microinches are also represented. Excluded are the reversal data that were obtained on a different type of body and the three points for which $Re_{\delta^*,TR}$ is negative. Considering the normal amount of scatter present in any transition data, the correlation appears to be good. The solid line in figure 5 will be discussed in a subsequent section.

The effect of nose shape as indicated in the X-17 reentry data obtained on hemispheres and on the GE 3.1 shape is shown in figure 6. For the GE shape, s is again the distance to transition, while r_n is the radius of the hemispherical nose segment. Laminar flow is sustained to slightly lower enthalpy ratios for the GE shape than for the hemisphere.

DISCUSSION OF CORRELATION

Application to Previously Contradictory Results

Wind-tunnel transition results obtained on a cone capped with a 1.40-inch-diameter spherical segment were reported in reference 8. The enthalpy ratios were of the same order as those for the PARD and HTV flights, and the momentum-thickness Reynolds number at the sonic point was about 375. These conditions caused transition in flight; yet the flow on the entire spherical segment in the tunnel tests was always laminar. However, when these results are examined in terms of the

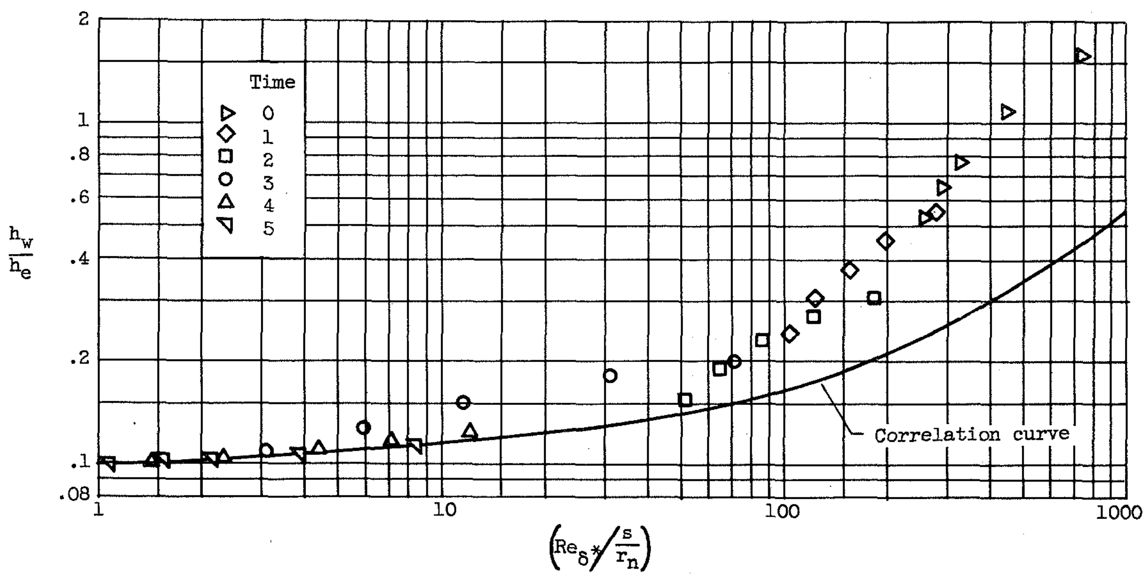
present correlation, it is apparent that the flow should have been laminar. The solid line in figure 5 represents the values of h_w/h_e and $\left(Re_{\delta^*}\Big/\frac{s}{r_n}\right)$ on the spherical segment of the wind-tunnel model. This line is well within the laminar region of the present correlation.

Results that hitherto have been unexplained by the correlations suggested in references 2 and 3 are the X-17 exit data obtained during the R-9 flight. Under exit conditions, the enthalpy ratio was relatively high and the free-stream Mach number was low; this yielded transition results similar to those of the PARD flights. Significant portions of the R-9 trajectory are reproduced in figure 7 in terms of the present correlation. It should be noted that the flow is turbulent only in the vicinity of the correlation curve, both in the exit and in the reentry phase of the trajectory. The fact that the exit data do not agree as well with the correlation as the reentry data can be attributed to the uncertainties present in the exit flight data (see ref. 3 for a detailed discussion). In fact, if possible time discrepancies are considered, much better agreement is possible between the correlation and the exit data.

The Prediction of Transition

It has been demonstrated that all available transition data on cooled hemispheres can be correlated in terms of $\left(Re_{\delta^*}\Big/\frac{s}{r_n}\right)_{TR}$. The question naturally arises as to how successful this correlation is in predicting transition. Unfortunately, in many cases it is not possible to determine the exact location where transition will occur, but generally it is possible to predict the lowest possible enthalpy ratio where laminar flow can be expected.

If, at a given time of flight, all points of a hemisphere lie above the correlation curve, the flow should be laminar. If, on the other hand, all points fall below the curve, the flow should be turbulent. However, if points on the forward portion of the body approach the correlation curve (without crossing it) while the rearward points do not, the flow over the entire body still may be laminar. This observation is illustrated with the aid of the following sketch of an X-17 trajectory:



In this sketch the solid line represents the correlation curve, and the symbols represent various body positions at a given time t during reentry. At the times $t = 0$ and $t = 1$, the entire body is above the correlation curve, and transition should not, and does not, occur. At $t = 2$, 3, and 4, the forward portions of the body approach the correlation curve, and transition might be expected. Yet, in flight, transition did not occur until $t = 5$, when the entire hemisphere fell along the correlation curve.

As pointed out earlier, the correlation is not sensitive to moderate amounts of surface roughness. This fact, however, does not imply that the location of transition on the nose portion of the body is independent of roughness. The aforementioned sketch indicates that, at the time when transition occurred, all stations along the body fell on the correlation curve; hence, the location of transition could be altered by roughness and still fall along the correlation curve. This discussion does not preclude the possibility that a larger amount of roughness could alter the correlation curve.

In spite of the fact that the proposed correlation cannot be used to predict the exact location of transition, its implications concerning the state of the boundary layer on the reentry body of a 5500-mile-range ballistic missile are serious. Presented in figure 8 in terms of the correlation parameters is the trajectory of a 5500-mile-range

ballistic missile with $\frac{W \sin \alpha}{C_D A} = 133$. The calculation has been made for the 20° and 80° stations on a 6-foot-diameter hemisphere at a constant wall temperature of 500° R. In order to determine the effect of temperature level, conditions at the 20° station also have been computed for a constant wall temperature of 2000° R. An examination of figure 8 shows that the enthalpy ratio on such a body will, at times, be well below any of the enthalpy ratios thus far obtained. Therefore, based on an extrapolation of the present correlation, transition is to be expected on the body during a large portion of the reentry flight. In drawing this conclusion, however, it must be realized that the extrapolation of transition results always is dangerous, and that the present correlation may not really apply to very low enthalpy ratios of ballistic missile reentry. However, the correlation should apply at the higher enthalpy ratios that occur at altitudes corresponding to peak heating rates. Moreover, although it is recognized that surface roughness may affect the location of transition, it is quite evident from figure 8 that transition cannot be avoided by making a body exceedingly smooth.

CONCLUDING REMARKS

A correlation of transition on highly cooled blunt bodies has been presented. The significant parameters in this correlation are the ratio of wall to local-stream enthalpy, displacement-thickness Reynolds number, and location of transition. This correlation is successful in explaining previously contradictory transition results. However, although the correlation can be used to predict the wall to local-stream enthalpy ratio below which turbulent flow is expected, it cannot be used to predict the exact location of transition on a body. Specifically, the following conclusions may be drawn:

1. Decreasing the wall to local-stream enthalpy ratio promotes early transition on blunt bodies. The early transition on blunt bodies and the transition-reversal phenomenon observed on slender bodies exhibit similar trends.

2. The transition correlation is insensitive to moderate amounts of surface roughness; this indicates that the enthalpy ratio necessary to promote transition anywhere on the body is unaffected by moderate roughness. However, the location of transition, once it does occur, may be affected by roughness.

3. The proposed correlation suggests that transition will occur on a blunt body of a 5500-mile-range intercontinental ballistic missile during a large portion of the reentry flight.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 15, 1957

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TABLE I. - SUMMARY OF DATA

Reference	Shape	φ_T, deg	s/r_n	M_1	$Re_{D,1}$	h_w/h_e	Re_θ	Re_{δ^*}	$Re_{\delta^*}/\frac{s}{r_n}$	$k\times10^6$	r_n, in.	Comments
2	Hemisphere	20	0.349	11.5	20.2×10^6	0.17	286	42.4	122.0	2	4.5	X-17 R-2
		30	.524	12.0	19.6	.15	420	37.7	72.0	2	4.5	
		20	0.349	10.9	12.7	0.13	240	13.8	39.5	2	4.5	X-17 R-8
		30	.524	10.3	10.6	.12	325	6.7	12.8	↓	↓	
		40	.698	9.9	9.4	.13	397	15.4	22.0	↓	↓	
		20	0.349	12.0	6.3	0.095	163	-5.7	-16.2	30	4.5	X-17 R-9
		30	.524	13.5	13.9	.11	311	2.4	4.6	1	↓	
		40	.698	13.7	12.0	.095	384	-12.6	-18.0	1	↓	
		50	0.873	12.4	23.6	0.12	684	8.1	9.3	1/2	4.5	X-17 R-11
		50	.873	11.8	13.0	.12	566	6.7	7.7	6	↓	
		60	1.047	12.4	21.9	.11	714	-7.2	-6.9	1/2	↓	
		22.5	0.393	11.1	15.4	0.127	285	11.8	30.1	20	4.5	X-17 R-22
		30.0	.524	10.9	14.4	.126	360	6.7	12.9	↓	↓	
		37.5	.655	9.4	9.3	.140	370	23.9	36.5	↓	↓	
		52.5	.916	9.5	7.2	.135	445	28.2	30.8	↓	↓	
		52.5	.916	10.7	13.6	.123	580	6.7	7.3	6	↓	
		52.5	.916	10.7	13.6	.123	580	6.7	7.3	1/2	↓	
		30.0	0.524	4.36	9.8	0.282	387	170	324	2	3.0	HTV RD1
		45.0	.785	3.98	9.8	.321	553	312	397	2	3.0	
		52.5	0.916	3.94	12.0	0.520	754	763	833	2	3.0	HTV RD3
		60	1.047	3.97	12.4	.450	875	610	583	2	3.0	
		45	0.785	2.58	7.8	0.58	596	681	868	11	3.0	HTV RD8
		30	.524	2.58	7.8	.62	398	452	863	---	3.0	
	Hemisphere (ablation)	22.5	0.393	3.33	9.9	0.45	319	277	705	---	3.0	HTV RD10
		15	.262	4.00	11.7	.38	216	143	546	---	↓	
		15	.262	4.97	13.9	.42	215	162	618	---	↓	
	Hemisphere-cone $\theta_c = 25^\circ$	19.4	0.338	2.50	9.8	0.71	310	475	1405	25	4.44	PARD flight
		19.4	.338	3.00	11.5	.63	320	419	1240	25	4.44	
		20.6	0.360	3.50	13.0	0.58	340	396	1100	25	4.44	PARD flight
		23.3	.406	4.00	14.4	.59	360	424	1044	↓	↓	
		23.3	.406	4.70	16.1	.57	370	425	1047	↓	↓	
	Hemisphere-cylinder	9.6	0.167	3.05	12.6	0.54	159	168	1006	25	4.00	PARD flight
		14.0	.244	2.00	9.0	.69	268	395	1619	↓	↓	
		15.2	.266	2.80	11.9	.55	294	320	1203	↓	↓	
		15.8	.276	2.50	11.1	.58	292	336	1217	↓	↓	
		30.3	.528	2.80	11.3	.95	574	1244	2356	↓	↓	
	Hemisphere-cone θ_c = 14.5	38.2	0.667	3.14	24.1	0.59	804	962	1442	2	6.5	PARD flight
		39.0	.681	2.97	23.2	.62	798	999	1467	↓	↓	
		41.2	.719	2.80	22.2	.67	794	1073	1492	↓	↓	
6	Hemisphere-cylinder	<11.5	<0.201	2.07	6.6	0.70	<144	<225	1119	5	4.5	NACA Lewis flight
2	GE 3.1	38.0	0.524	7.9	20.6	0.260	484	207	395	1/2	3.4	X-17 R-17
		↓	.764	8.3	21.0	.268	548	248	325	↓	↓	
		↓	.945	8.7	21.5	.193	608	153	162	↓	↓	
		↓	.945	10.7	15.8	.130	500	35.5	37.6	↓	↓	
		38.5	0.510	11.4	23.0	0.133	450	30.6	60.0	1/2	3.4	X-17 R-18
		↓	.939	11.5	20.9	.123	535	36.4	38.8	↓	↓	
		↓	1.148	10.0	12.4	.120	460	35.4	30.8	↓	↓	
		↓	1.358	10.0	12.4	.119	500	37.5	27.6	↓	↓	
		37.7	0.520	14.0	9.0	0.094	270	7.3	14.0	30	3.4	X-17 R-21
		↓	.520	13.0	7.0	.091	240	3.4	6.5	1/2	↓	
		↓	.701	13.3	7.5	.090	280	4.2	6.0	30	↓	
		38.0	.945	13.0	7.0	.088	300	-4.6	-4.9	30	↓	
		38.0	.945	12.0	5.8	.082	285	-4.8	-5.1	1/2	↓	
		37.7	0.520	10.9	15.4	0.124	394	27.6	53.1	5	3.4	X-17 R-23
		↓	.520	10.6	14.0	.126	375	26.6	51.1	15	↓	
		↓	.701	10.2	12.0	.120	386	28.6	40.8	5	↓	
		↓	.701	10.6	14.0	.116	415	29.5	42.1	15	↓	
		38.0	.949	10.2	12.0	.117	430	31.8	33.5	5	↓	
		38.0	0.949	10.6	14.0	0.124	467	33.2	34.9	15	3.4	
		39.0	1.148	9.8	10.2	.125	438	33.7	29.4	5	↓	
		39.0	1.148	9.6	9.7	.125	420	33.2	28.9	15	↓	
		39.7	1.358	9.8	10.2	.130	460	35.4	26.1	5	↓	
		39.7	1.358	9.5	9.2	.124	438	35.0	25.8	15	↓	
5	Cone-cylinder $\theta_c = 4.75^\circ$	85.25	32.0	3.12	0.98	0.451	334	747	------	12	0.094	NACA Lewis wind-tunnel tests
		↓	↓	↓	2.17	1.262	501	2239	↓	↓	↓	
		↓	↓	↓	1.69	.662	442	1246	↓	↓	↓	
		↓	↓	↓	1.59	.731	429	1291	↓	↓	↓	
		↓	↓	↓	1.17	.480	363	841	↓	↓	↓	
		↓	75.0	↓	1.17	.474	567	1316	↓	↓	↓	
		↓	↓	↓	1.69	.720	691	2058	↓	↓	↓	
		↓	↓	↓	1.59	.849	670	2367	↓	↓	↓	
		↓	↓	↓	.98	.460	527	1192	↓	↓	↓	
		90.0	135.0	↓	.98	.524	835	2166	↓	↓	↓	
		↓	↓	↓	1.17	.528	908	2365	↓	↓	↓	
		↓	↓	↓	1.69	.716	1107	4562	↓	↓	↓	
		↓	↓	↓	1.59	.865	1073	3788	↓	↓	↓	
3	Hemisphere	50	0.873	2.67	7.70	0.675	648	824	943	30	4.5	X-17 R-9 Exit data (18 to 25 sec turbulent flow)
		50	.873	5.15	6.60	.352	488	267	306	30	4.5	

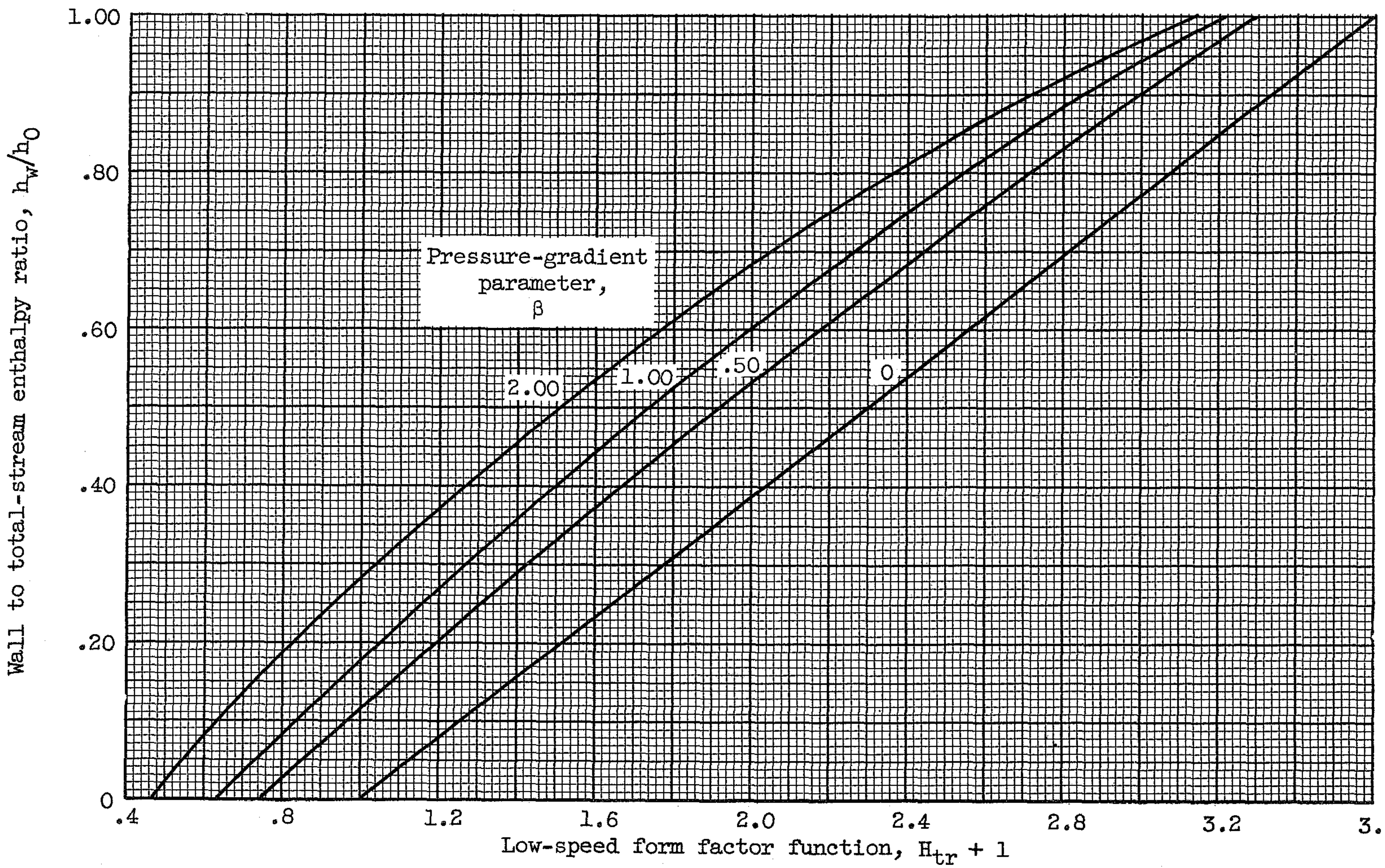


Figure 1. - Variation of form factor function with pressure gradient and enthalpy ratio.

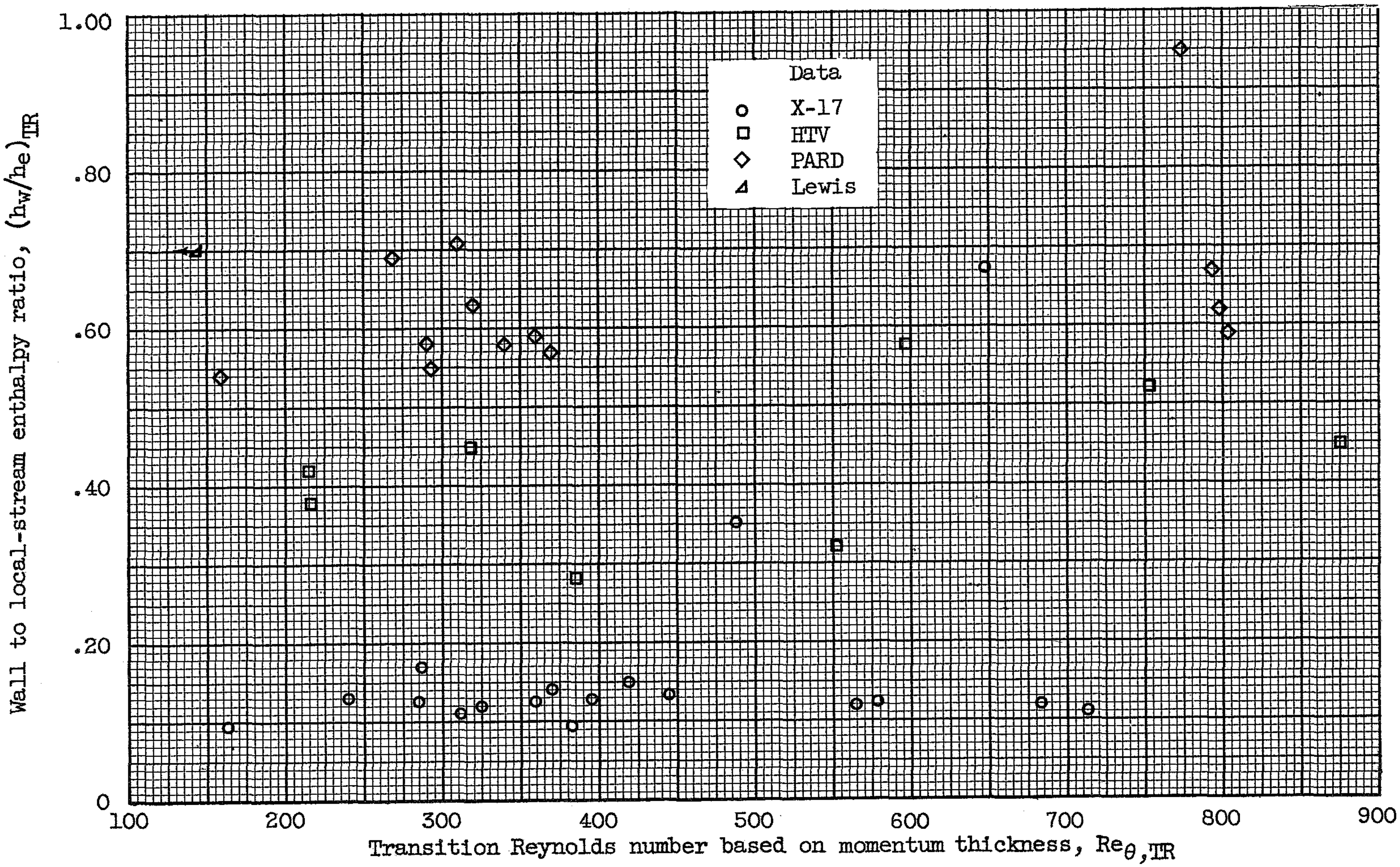
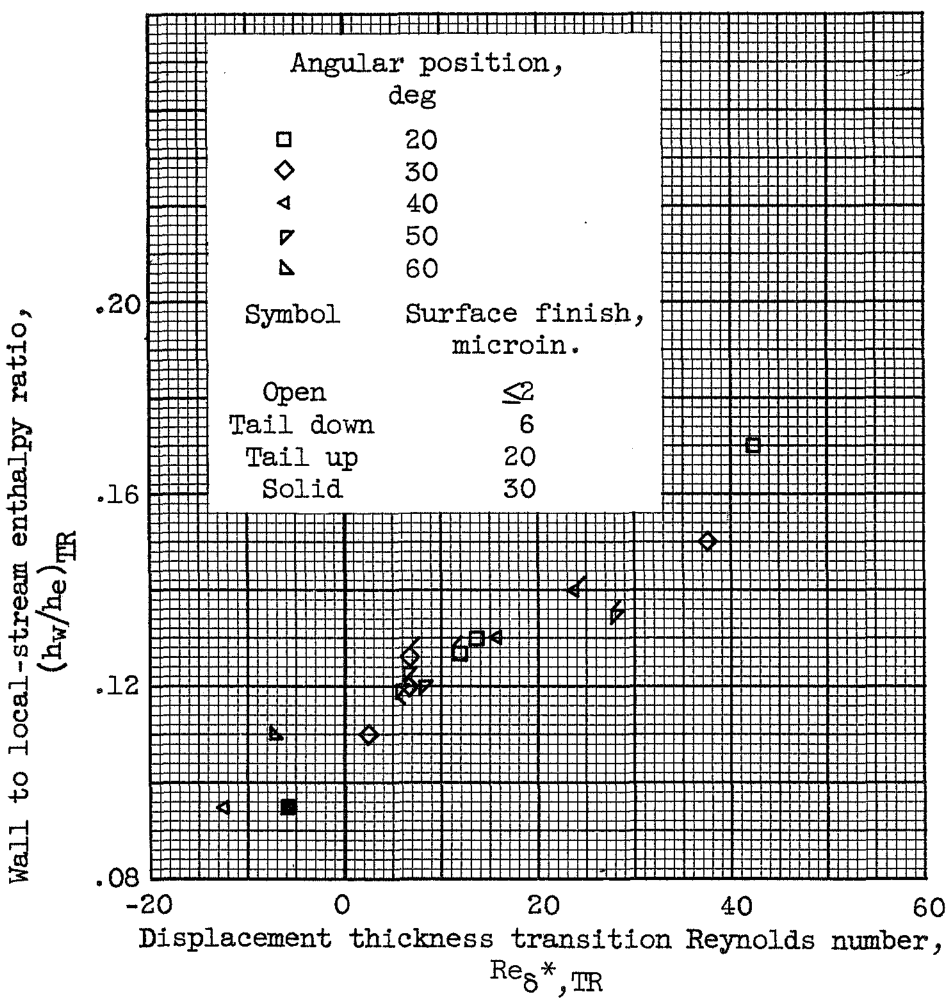


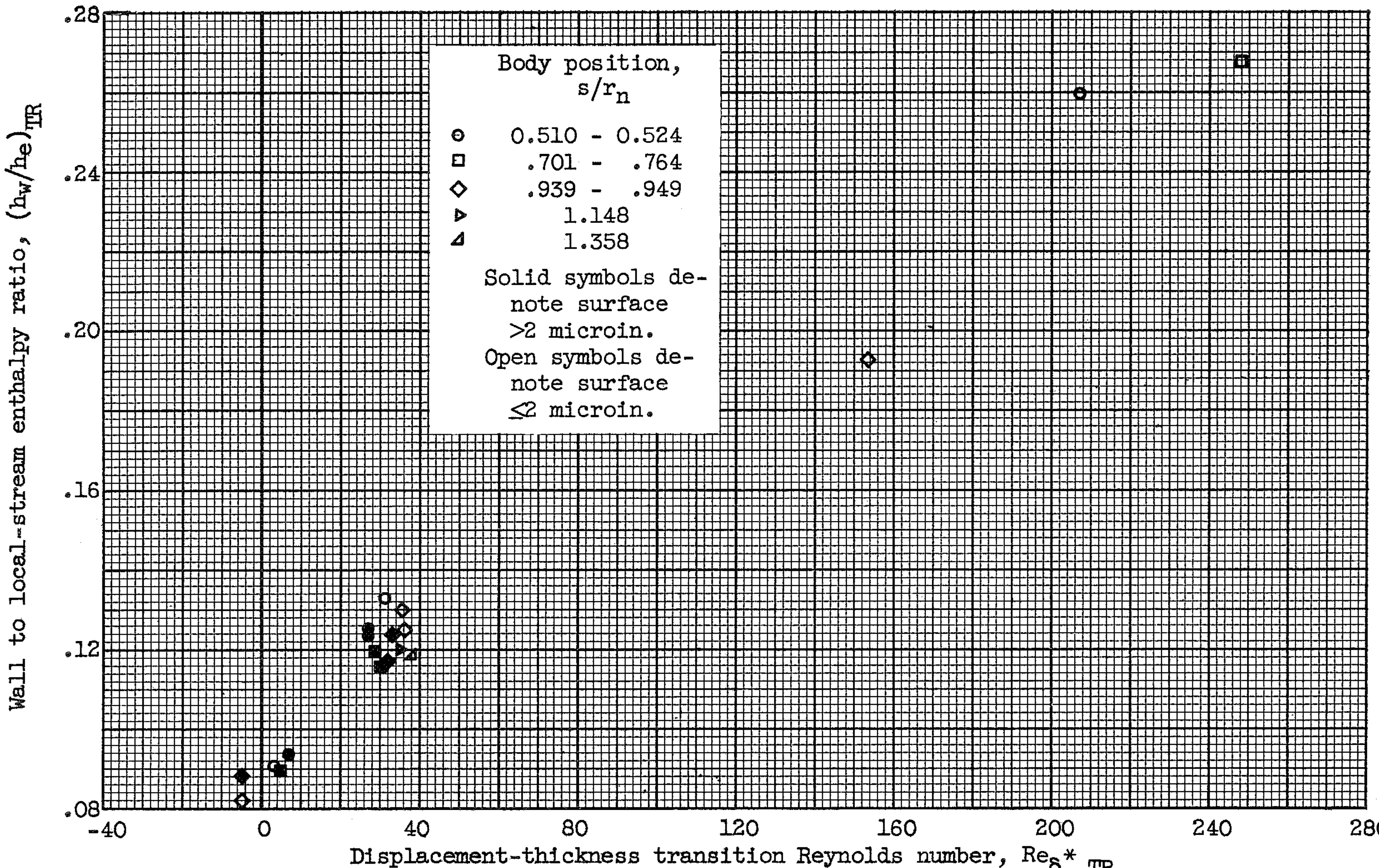
Figure 2. - Boundary-layer transition on hemispheres, as obtained in free flight.



(a) Hemisphere shape.

Figure 3. - Transition on X-17 research test vehicle during reentry.

SECRET



(b) G.E. 3.1 shape.

Figure 3. - Concluded. Transition on X-17 research test vehicle during reentry.

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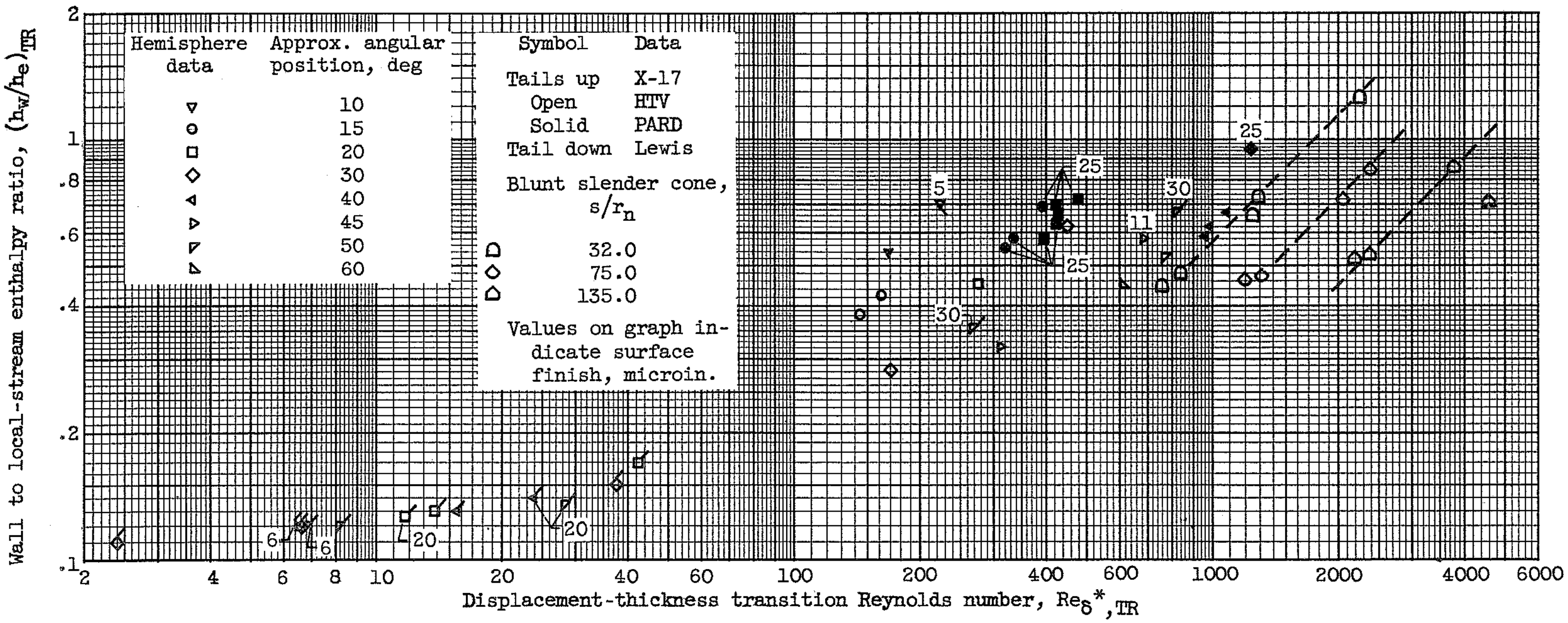

Figure 4. - Attempted correlation of hemisphere data in terms of displacement-thickness Reynolds number.

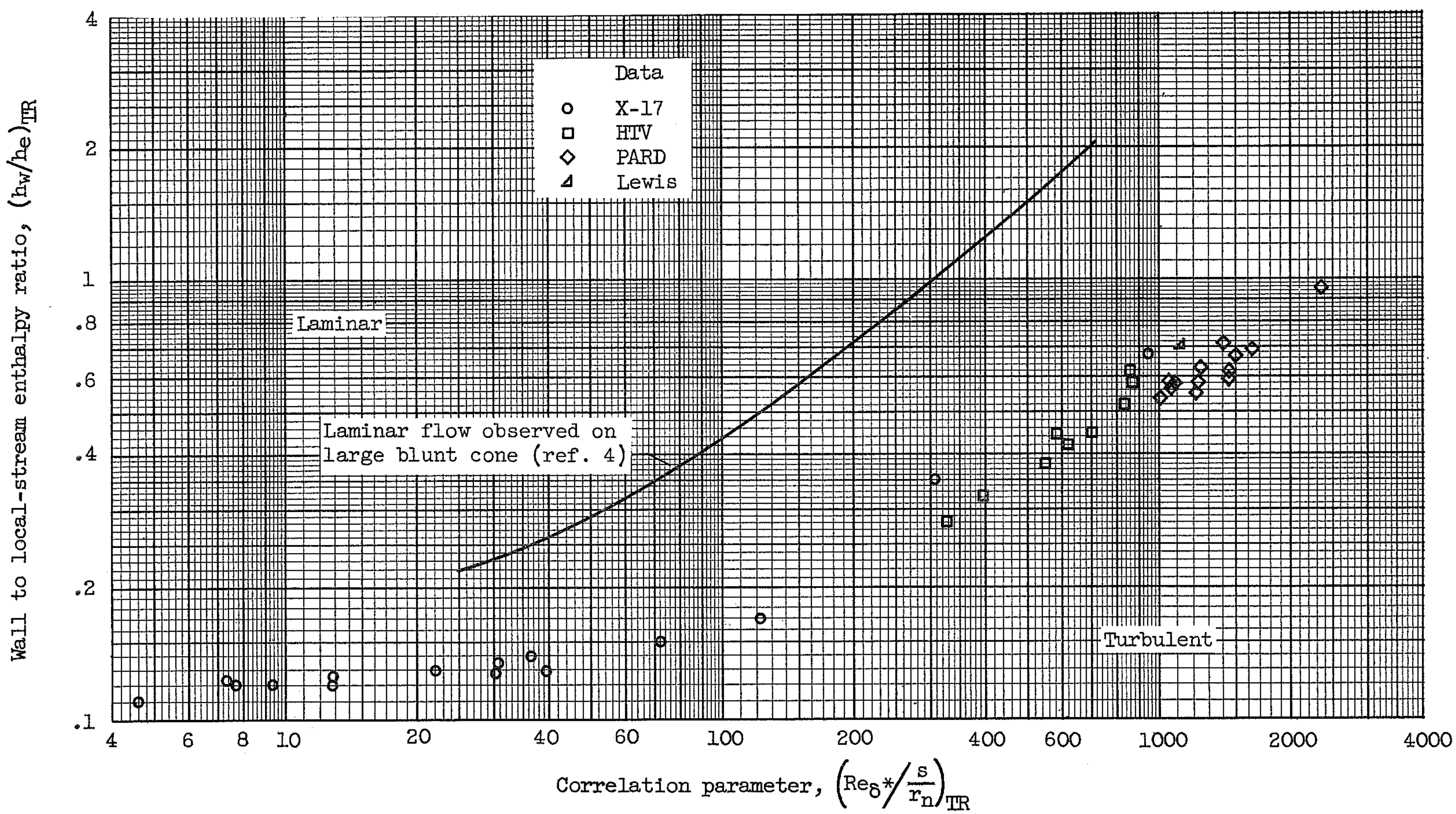

Figure 5. - Correlation of transition data obtained on hemispheres.

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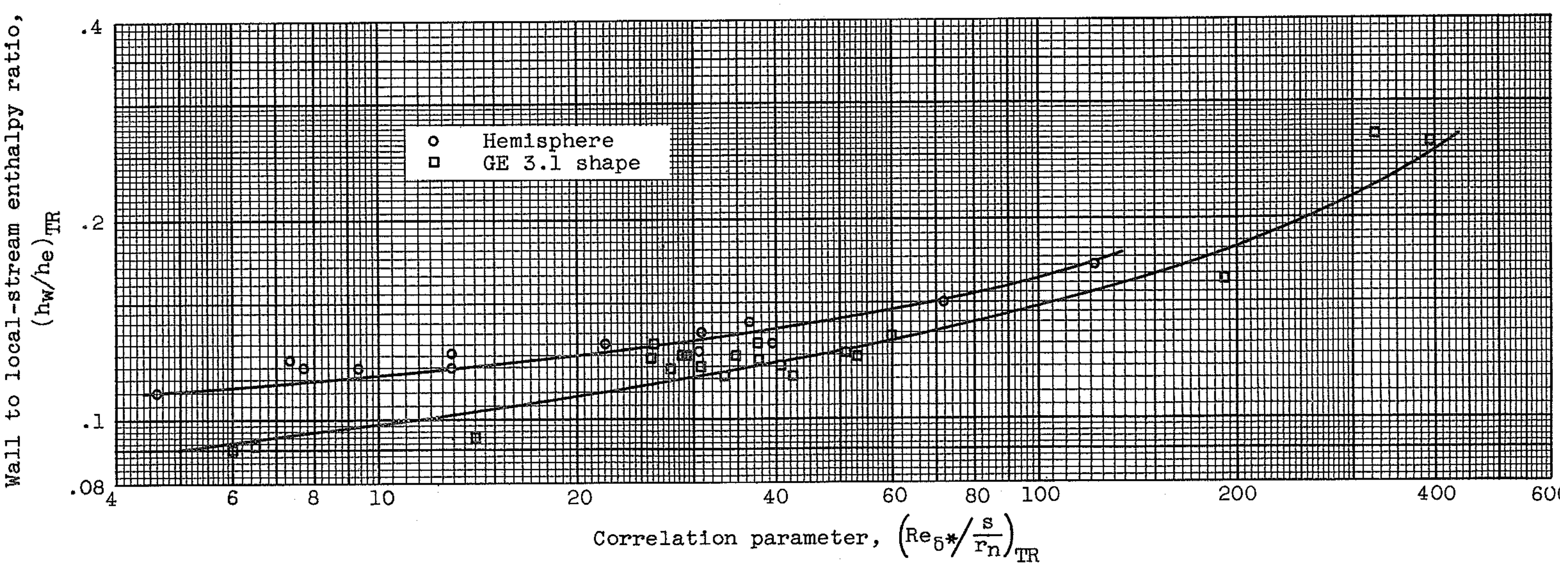

Figure 6. - Variation of correlation parameter on X-17 reentry body hemisphere and GE 3.1 shape.

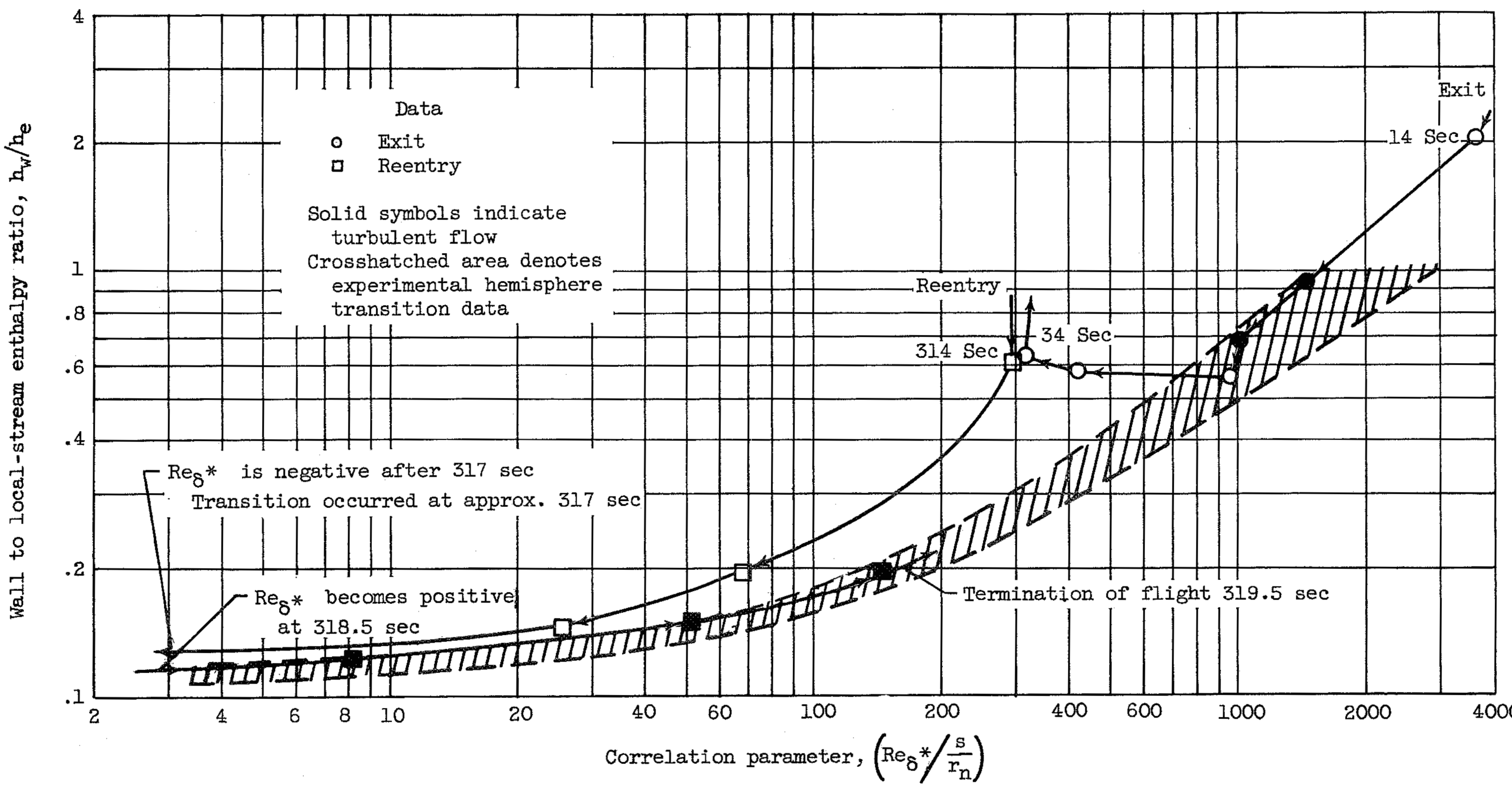

Figure 7. - Conditions at 90° position during exit and reentry of X-17 R-9 flight.

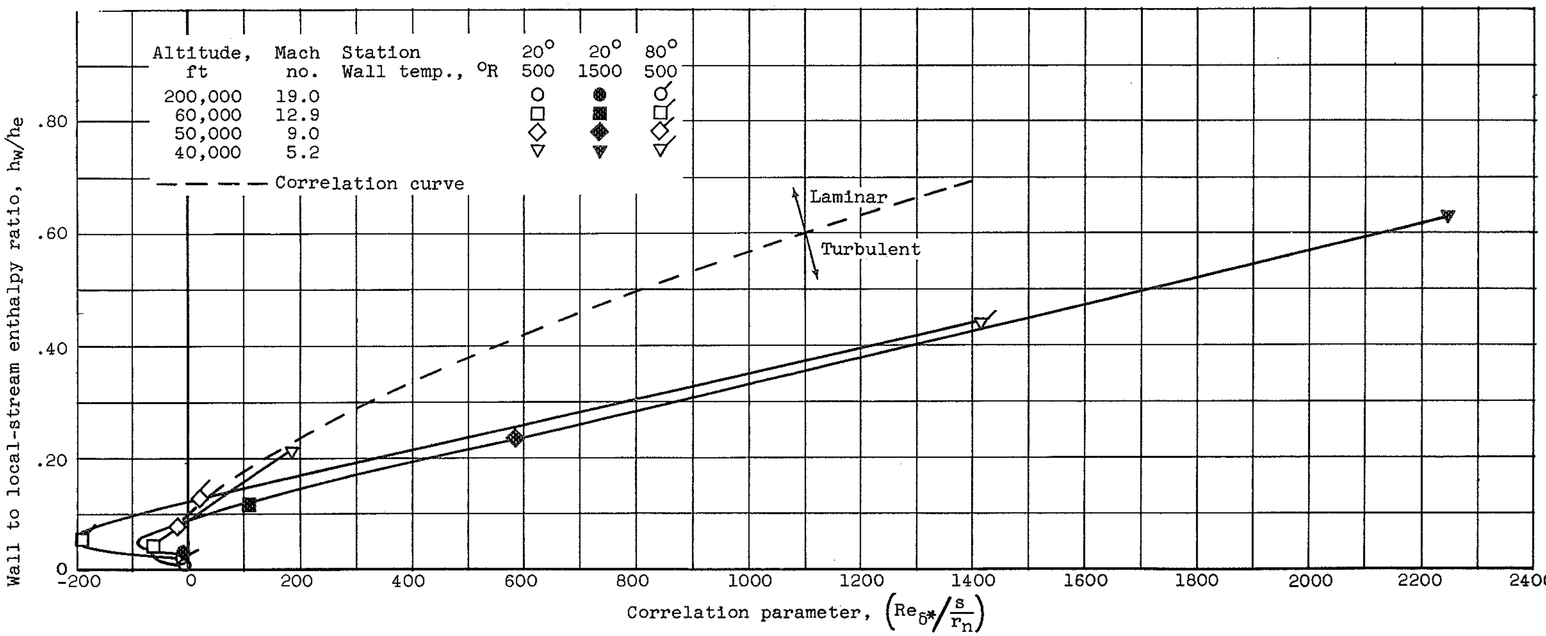

Figure 8. - Conditions at 20° and 80° positions during reentry of a 6-foot-diameter hemisphere ballistic missile (trajectory obtained from ref. 9). $\frac{W \sin \alpha}{C_D A} = 133$.

Unclassified when detached from rest of report

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maa - 10/15/57